
Spitzer's View of Planetary Nebulae

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Summary. The *Spitzer Space Telescope*, NASA's Great Observatory for infrared astronomy, has made available new tools for the investigation of the infrared properties of planetary nebulae. The three instruments onboard, including the Infrared Array Camera (IRAC), the Multiband Imaging Photometer for *Spitzer* (MIPS), and the Infrared Spectrograph (IRS), provide imaging capability from 3.6 to 160 μm , and low and moderate resolution spectroscopy from 5.2 to 38 μm . In this paper I review recent *Spitzer* results concerning planetary nebulae and their asymmetrical structures.

Key words: Planetary Nebulae, *Spitzer Space Telescope*, IRAC, MIPS, IRS, Infrared

1 The *Spitzer* Mission

The *Spitzer Space Telescope* [31] (*Spitzer*), launched in August 2003, is the final component of NASA's "Great Observatories", and its instruments take advantage of the gains in infrared detector technology since the *IRAS* and *ISO* missions to achieve unprecedented sensitivity at infrared wavelengths not available from ground-based observatories. The Infrared Array Camera [11] (IRAC) obtains images in four bands at 3.6, 4.5, 5.8, and 8.0 μm . The Infrared Spectrograph [18] (IRS) obtains low or moderate resolution spectra over the range of 5.2 – 38 μm . The Multiband Imaging Photometer for *Spitzer* [24] (MIPS) obtains images at 24, 70, and 160 μm as well as a spectral energy distribution (SED) between 50 and 100 μm . The telescope is cooled passively and by helium boil-off vapor to 5.5K, providing a low-background system that is limited only by the detector properties and the astronomical background. *Spitzer* allows us to build on the groundbreaking work done by *IRAS* and *ISO*, providing improved spatial resolution and a >100+ fold increase in sensitivity.

Spitzer is an observatory for the community – most of the time is awarded to General Observer (GO) programs, including "Legacy" projects which have

no proprietary time. Most of the *Spitzer* data, including the original guaranteed time (GTO) programs and observations from the first three GO cycles, are now publicly available. There are also further opportunities for submitting new observing proposals. The next call for proposals (Cycle 5) will happen in mid-August 2007, with a proposal deadline of November 16, 2007. This will be the last proposal call for the cryogenic mission. The helium cryogen is anticipated to last until March 2009. After the cryogen has been depleted, the telescope and instruments are expected to reach an equilibrium temperature of $\sim 30\text{K}$, which will allow the IRAC 3.6 and $4.5\ \mu\text{m}$ bands to continue to operate for several more years. Planning is now underway for a “warm mission” which would have an open call for proposals in the fall of 2008.

2 Application of IR Imaging and Spectroscopy to PNe

Several examples of the importance of IR imaging and spectroscopy to the study of planetary nebulae (PNe) were presented at last year’s IAU Symposium #234 in reviews of IR imaging [15] and spectroscopy [10]. Most of those examples apply to the *Spitzer* data, including the ability to penetrate into optically obscured regions to resolve structures in the nebula and near the central stars; to measure the emission from dust and small grains and determine their composition, properties, and explore aspects of dust formation; to detect emission from neutral material such as H_2 and determine the conditions responsible for its excitation; and to observe lines of different ionization states in the IR to determine abundances and physical conditions in the nebulae.

The higher sensitivity of the *Spitzer* instruments allow for the first time a large sample of Galactic and extragalactic PNe to be studied in the mid-infrared. The $5' \times 5'$ field of IRAC and MIPS allow for relatively rapid imaging of large fields at high sensitivity to map the distribution of warm and cool dust throughout the nebula and halos of PNe. The IRS can make pointed observations and also has a spectral mapping mode which can be used to produce images in various lines and dust features to determine their spatial distribution.

3 Available *Spitzer* data

Spitzer is now in its fifth year of operation, and a majority of the data obtained is now public. The easiest way to find out whether a source has been observed and what data are available is to use the Leopard archive query program available from the SSC website¹. A list of all approved programs is also provided, which can be used to search for projects associated with PNe.

There are several Legacy, GTO, and GO programs that have relevance to PNe. The GLIMPSE [1] and MIPS GAL surveys cover the inner $\pm 65^\circ$ of

¹ <http://ssc.spitzer.caltech.edu>

the Galactic disk with IRAC and MIPS bands, respectively. The GLIMPSE data have already been used to find new PNe [4] and study previously known PNe [21, 5]. The SAGE survey imaged the LMC with IRAC and MIPS at sufficient sensitivity to detect most of the PNe in that galaxy [16]. An IRAC and MIPS survey of the star-forming body of the SMC was performed early in the mission (S³MC [2]), and the approved SAGE-SMC program will map a wider field to map the entire SMC with IRAC & MIPS at a similar sensitivity to the LMC. The approved SAGE-SPEC Legacy project will survey over 100 objects found in the SAGE survey, including 12 PNe, 7 Post-AGB, and 72 AGB stars & candidates.

There are several GTO programs that have focused on PNe. A series of IRAC GTO programs have imaged over fifty PNe [12] (program IDs (PIDs) 68, 30285, 40020). Another 16 PNe with dual dust chemistry are to be observed in Cycle 4 (PID 40115). Several other IRAC programs study young PNe, Luminous Blue Variables, and PNe halos. The MIPS GTO program (PID 77) imaged 10 PNe with MIPS (e.g., [28]), and obtained IRS spectra of several objects. There are IRS GTO programs that study PNe in the LMC [7] and SMC, and in the Galactic Bulge (PIDs 103, 30482, 30550).

In a quick check of the list of approved programs before this conference, I found 14 GO programs directly associated with PNe, and there are no doubt more that contain data useful to the study of PNe. Most of the GO programs use the IRS to obtain spectra to study abundances, dust properties and evolution, and metallicity effects. There are also programs that use MIPS to examine the cool dust in PNe.

4 IRS Results

A discussion of the IRS results since launch was included in the review of IR spectroscopy of PNe by Bernard-Salas [10] at IAU Symposium #234. The first published IRS spectrum of a PN was of SMP83 in the LMC [7], which demonstrated the instrument sensitivity and the capability to determine abundances in PNe as distant as in this neighboring galaxy. Another observation of a LMC PN from the IRS GTO program was of SMP LMC 11 [9]. The optical properties of this object resemble that of a PN, but its spectrum implies a pre-planetary nebula (PPN). The spectrum shows no polycyclic aromatic hydrocarbon (PAH) emission but many molecular absorption bands, and the first detection of C₄H₂, C₆H₂, and C₆H₆ absorption in an extragalactic object. These molecules are the building blocks from which more complex hydrocarbons are produced. The spectrum is similar to that seen by *ISO* in the PPN AFGL 618 [3]. SMP LMC 11 shows a lack of nitrogen-based molecules (apparently a trend in LMC/SMC objects) which are prominent in Galactic objects.

The post-AGB star MSX SMC 029 has also been observed with IRS [19]. The spectrum is dominated by a cool dust continuum (~ 280 K). Both PAH emission and absorption from C₂H₂ are present. Strong absorption features

from C_2H_2 , C_4H_2 , HC_3N , and C_6H_6 in the $13 - 16 \mu\text{m}$ range are also seen, similar to those in the post-AGB objects AFGL 618 and SMP LMC 11. The PAH features in the spectrum are unusual, with a peak emission in the $7 - 9 \mu\text{m}$ complex beyond $8 \mu\text{m}$ instead of near $7.7 - 7.9 \mu\text{m}$. Also, the $8.6 \mu\text{m}$ feature is as strong as the C – C mode feature. The $11.3/8 \mu\text{m}$ ratio suggests that the PAHs either have a low-ionization fraction or are unprocessed, which implies that MSX SMC 029 has only recently evolved off the AGB branch.

Another investigation of the PNe in the Magellanic Clouds has been performed which examined a total of 16 SMC and 25 LMC PNe with the IRS [26, 27]. They report that about half of the PNe show either C-rich or O-rich dust compounds. They also find that all PNe with carbonaceous dust are either round or elliptical while all PNe with O-rich dust are bipolar. The IRS spectra of symmetric and asymmetric PNe are apparently extremely different, showing a tight connection between dust type and morphology.

5 MIPS Results

The MIPS observations of PNe have been able to trace the distribution of the cool dust, as well as forbidden line emission from the ionized gas. In the first MIPS results reported on NGC 2346 [28], the emission is seen to be strongest in the equatorial plane and the walls of the bipolar lobes of the nebula, and is in general more extended than the optical emission. The data can be fitted using a model with two components with temperatures of 60K and 25K. A central peak is seen in the $24 \mu\text{m}$ image, which is likely the dust causing the deep fading of the central star in the optical. Polar tips are seen in the bipolar lobes which indicate a more collimated component of the mass loss. A toroidal structure is seen in the equatorial plane at $70 \mu\text{m}$. The angular offset and the color difference in the torus between 24 and $70 \mu\text{m}$ indicates the PN is not completely axisymmetric and there has been some change in position angle, which could have been caused by the binary companion. The PN NGC 650 was also observed with MIPS [30], and it was found that the $24 \mu\text{m}$ emission is largely due to the [O IV] line at $25.9 \mu\text{m}$, whereas the 70 and $160 \mu\text{m}$ flux is due to $\sim 30\text{K}$ dust continuum emission in the remnant AGB shell. The far-IR nebula structure suggests that the enhancement of mass loss at the end of the AGB phase has occurred isotropically, but has ensued only in the equatorial directions while ceasing in the polar directions.

The MIPS observations of the Helix found an unresolved central source with excess thermal continuum emission at 24 and $70 \mu\text{m}$, as well as in the IRAC $8 \mu\text{m}$ band [29]. They conclude that the emission is most likely from a dust disk with temperatures of $90 - 130\text{K}$, distributed from $35 - 150 \text{ AU}$ from the central star. They speculate that this dust possibly arises from collisions of Kuiper Belt-like objects, or the breakup of comets from an Oort-like cloud that has survived the post-main sequence evolution of the star. The Helix also has an inner bright bubble at $24 \mu\text{m}$ due to [O IV] which fills in the region

inside the main ring. The $160\ \mu\text{m}$ emission is primarily in the main ring, with an appearance similar to that at $8\ \mu\text{m}$.

6 IRAC Results

The first IRAC images of PNe [12, 14] showed that *Spitzer* could probe the faint extended emission from ionized gas, warm dust, PAHs, and H_2 in relatively short integration times. Some typical results are shown in Figure 1. The appearance of the extended emission in the IRAC bands is similar to the optical appearance in some cases, but often there are important differences. For example, in NGC 246 an unexpected “ring” of emission is prominent in the longer IRAC wavelengths within the elliptical shell of the nebula [12].

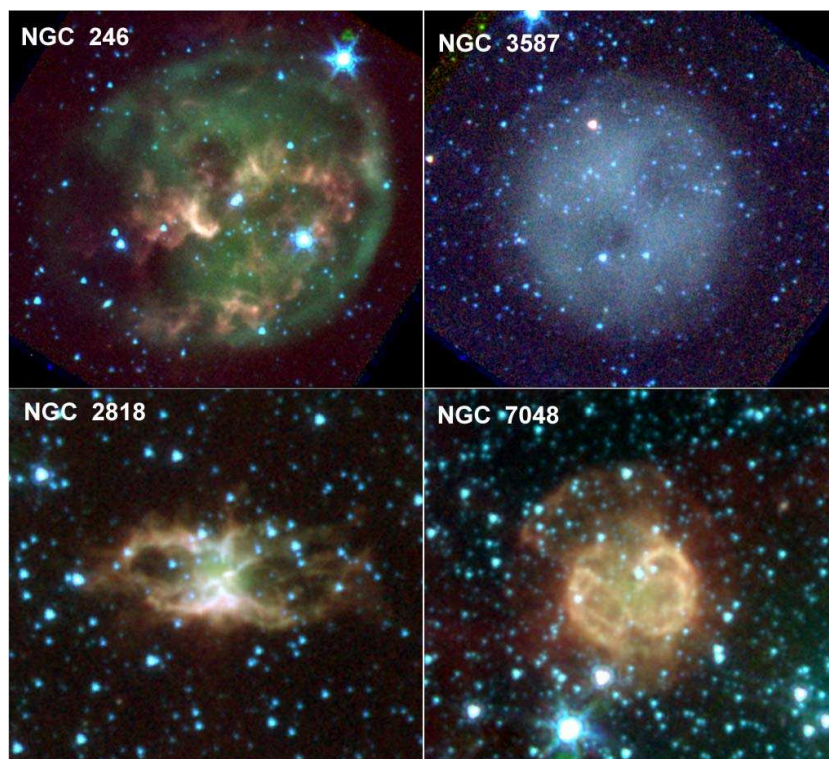
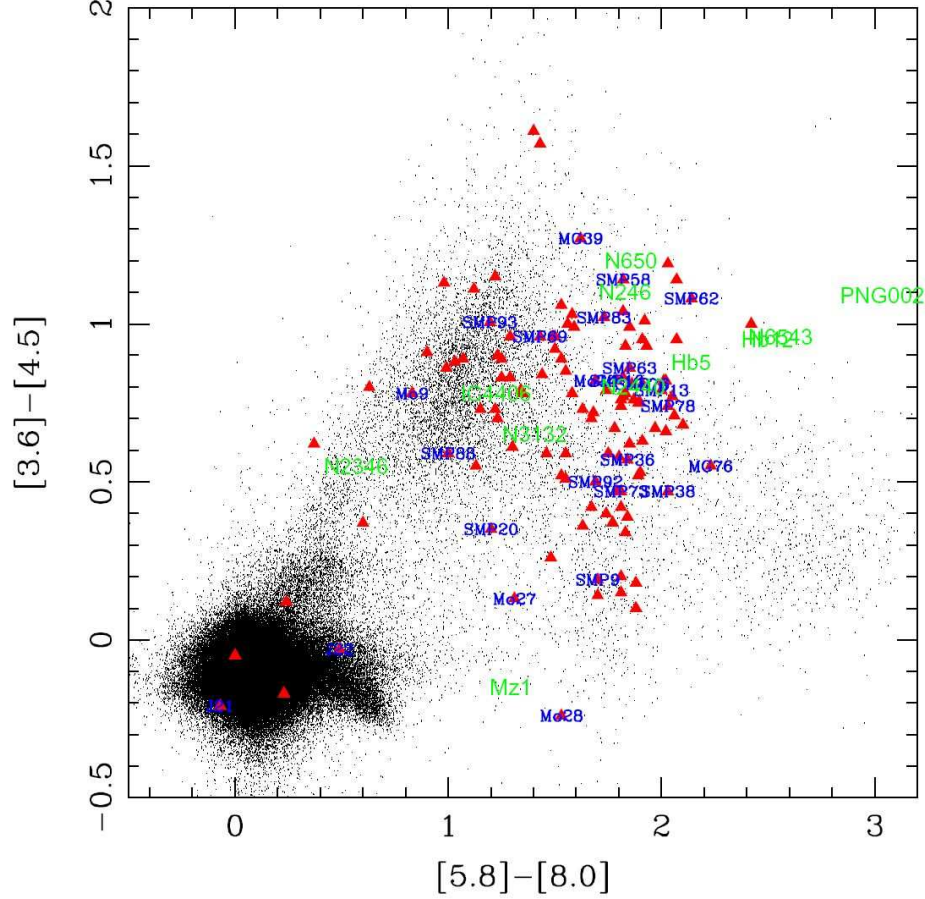


Fig. 1. IRAC color images of PNe NGC 246, NGC 2818, NGC 3587, and NGC 7048 [17]. In all images the 3.6 , 4.5 , and $8.0\ \mu\text{m}$ bands are assigned to blue, green, and red, respectively. North is up and East is to the left in all images.

In PNe that are dominated by H_2 emission, such as in NGC 6720, NGC 6853, and NGC 7293, the spatial distribution closely matches that of the

$2.12\ \mu\text{m}$ H_2 line emission [14]. Because the stellar and nebular free-free continuum is much reduced at the IRAC wavelengths, the emission from the halo and from the dust and molecular lines appear more prominent. The IRAC colors of PNe are red, especially in the 5.8 and $8.0\ \mu\text{m}$ bands [14, 16, 21] (see Figure 2), which separates them from main sequence and evolved stars, although they occupy a region of color-color space similar to young stellar objects and H II regions [32].



The GLIMPSE survey has yielded several results on PNe. The discovery of the new PN G313.3+00.3 has been reported based on the IRAC imaging and radio images which show the round PN shell [4]. The ability to see through the extinction in the plane, and the higher IRAC resolution compared to previous IR surveys were important in identifying the new PN. The positions of known PNe in the survey have been examined, and roughly one third have been detected [20, 21], even at a relatively shallow survey depth. Another set of objects with PNG classifications were found unlikely to be PNe, based on their IR morphology.

The known PNe in the LMC from the SAGE survey have also been analyzed [16] (see Figure 2). Approximately 75% of the optically-identified PNe were detected by IRAC and MIPS at the survey depth. Their IRAC colors were found to be similar to the set of Galactic PNe, and to depend on the dominant spectral characteristics of their mid-IR spectra as determined from their IRS spectra [8]. The IR PNe luminosity function (LF) for the LMC was found to follow the same functional form as the well-established [O III] LF, although there are several PNe with observed IR magnitudes brighter than the cut-offs in these LFs.

The IRAC images of the nearby PN NGC 7293 (The Helix) [13] resolve the famous cometary knots previously detected in optical images. The IRAC images are dominated by H₂ emission (as was first seen by *ISO* [6]), although the excitation mechanism is not clear [13, 23, 22]. In addition to the IR emission from the tips of the knots which are also bright in the optical, H₂ emission is detected from the tails of the knots in the IRAC images. The main rings are composed of a large number of clumps similar to the cometary knots but without the long tails, and radial rays of emission extend from the outer edge of the main ring into the outer halo.

7 Summary

Spitzer infrared observations of PNe are providing unique insights on the composition, ionization, structure, temperature, and relative location of ionized gas, dust, PAHs, and H₂ in the nebulae. A wealth of data exists in the *Spitzer* archive now, in large-area surveys and pointed observations of PNe. The final Call for Proposals for the cryogenic mission has been issued and they are due in November 2007. Act now if you have a need for new *Spitzer* observations!

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